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P WAVE PARAMETERS MEASURED AT THE MONTANA LASA

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TELEDYNE, INC.

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ABSTRACT

The raypath parameter, p, and the azimuth deviation of the source from the raypath direction have been computed from the first arrival P waves of over 600 earthquake events recorded at the Montana LASA during its first two years of operation. The epicenters of 247 of these events are located along a profile extending northwest of the reference station, LASA - A0, within the range of azimuth 300°-320°. The epicenters of 162 events are located along a profile toward the southeast in the range of azimuth 140°-160°.

The observed p and azimuth deviations of the northwest profile are compared to those from the southeast, showing: (1) large effects due to either crustal structure or regional velocity gradients in the upper mantle beneath LASA, and (2) variations suggesting a large difference in the velocity of P waves within the mantle between 700 and 2000 kilometers. Comparison or our observations with those of Chinnery and Toksöz confirm their suggestion of velocity discontinuities in the mantle; our data imply an additional velocity discontinuity at a depth of approximately 1500 km along the northwest profile.

THEORY

The observed arrival times of first arrival P waves recorded by a horizontal array of seismometers such as the one at LASA provide measurements that can be used to compute (1) the reciprocal horizontal phase velocity (p), and (2) the deviation of direction of arrival. The raypath parameter p is the magnitude of the slope of the travel-time curve, and the azimuth deviation is the angle between the back azimuth to the epicenter and the apparent arrival direction. Both of these wavenumber parameters yield information about the crust and upper mantle structure beneath the array and the variation of velocity in the mantle.

The first step in computing these quantities is to fit a plane wave front to the first arrival P waves. This is done by the least-squares method described below. Making the assumption that the wave front is planar imposes the following practical limitations on events studied: (1) the events which can be considered must occur at distances greater than 2900 km (26°) from the array: (2) the maximum dimension of the array must be less than 100 km as measured from the reference station.

The errors due to scatter in observed times can be reduced to a minimum by using an array with the largest possible diameter. The F-ring of subarrays at LASA has a diameter of 200 km, which is ideally suited for this purpose.

In order to derive the equations for the determination of p and the azimuth deviation by the least-squares method, it is necessary to consider the equation for the arrival time of a plane wave front. This may be expressed as:

$$T = t_x X + t_y Y + t_z Z$$

where:

t_x is the component of reciprocal velocity in the E-W direction;

t_y is the component of reciprocal velocity in the N-S direction;

t_z is the reciprocal vertical wave velocity;

X is station distance from the reference point in the E-W direction;

Y is station distance from the reference point in the N-S direction;

Z is station elevation relative to the reference point.

Taking the gradient of T (grad T) we obtain a vector in the direction of the incident ray which has a magnitude equal to the reciprocal propagation velocity:

$$\text{grad } T = t_x\underline{i} + t_y\underline{j} + t_z\underline{k}$$

where:

$\underline{i}$ is a unit vector in the E-W direction;

$\underline{j}$ is a unit vector in the N-S direction;

$\underline{k}$ is a unit vector in the vertical direction.

If we observe the arrival times of the first arrival P waves at a horizontal array of seismometers, then we can compute the magnitude and direction of p. To do this, one of the seismometers located near the geometric center of the array is taken as a reference. These relative delay times are recorded as either positive or negative with respect to the arrival time at the reference station. The station distances are also relative and fixed for all events.

The arrival time T_i at the i^{th} station is then given by:

$$T_i = t_x X_i + t_y Y_i + t_z Z_i$$

where the subscript i designates the i^{th} instrument in the array.

When the observations are limited to stations at the same elevation, this equation becomes:

$$T_i = t_x X_i + t_y Y_i \qquad i = 1,2,\ldots I \qquad (1)$$

where I is the number of stations in the array.

The reciprocal horizontal phase velocity components t_x and t_y are obtained initially by a simple least-squares calculation, assuming exact knowledge of the station locations.

After the components t_x and t_y have been obtained, the magnitude of the reciprocal horizontal phase velocity ($p = dt/d\Delta$) is found from:

$$p = (t_x^2 + t_y^2)^{1/2}$$

Then, the direction of arrival of the incident ray is found from:

$$\phi = \tan^{-1} (t_x/t_y)$$

where ϕ is the back azimuth angle of the measured direction of arrival.

When ϕ has been computed then the azimuth deviation can be determined. The azimuth deviation is the difference between ϕ and the apparent azimuth to the epicenter.

NORTHWEST PROFILE

The raypath parameter, p, and the azimuth deviation have been computed for over 600 earthquakes recorded at LASA during its first two years of operation. The epicenters of 247 events are located along a profile extending to the northwest in the range of azimuth 300°-320°. These are so distributed as to provide essentially continuous coverage of the distance range 26°-97°.

To reduce scatter in p and the azimuth deviation we consider only those events which satisfy the following criteria: (1) The event must have been clearly recorded at the reference station, A0, and at all four of the stations in the F-ring of subarrays (because the determination of the least-squares source of an event located within this range of azimuth depends critically on the delay times at subarrays F2 and F4); (2) The event must have been recorded at at least eight of the other 16 subarrays.

Five events along the northwest profile did not satisfy the second requirement because the delay times were not recorded at more than eight stations. Seventy-one events were omitted because one or more of the delay times from stations in the F-ring were missing due to instrumental failure. The remaining 171 events are included in the northwest profile.

Figure 1 shows the variation with distance of measured azimuth deviations along the northwest profile. The two important features of the observed variation are: (1) the average value of the azimuth deviations for all events along this profile is -0.5°, and (2) the variation in the azimuth deviations reflects the change in epicentral azimuth of these events. This becomes apparent when we examine the azimuth deviations as a function of azimuth along the profile.

For the northwest profile the epicenters in the distance range 32° and 47° are within the azimuth range 300°-305°. All

but four of the corresponding azimuth deviations have values between -0.5° and -2.0°. In the distance range 52°-75° all but one of the epicenters are between the azimuths 310°-and 317°, and all but three of the azimuth deviations corresponding to these events are between -0.5° and +1.1°. In addition, the value of the azimuth deviations changes most in the distance intervals 26°-32°, 47°-52°, and 75°-97° where the corresponding epicentral azimuths are undergoing the most change.

Figure 2 shows the variation of p with distance for events in the northwest profile. The observations provide almost complete coverage between 26° and 97°. With the exception of the abrupt discontinuity in the curve at 87°, all but five of the observed values of p are within ±0.05 seconds per degree of the smooth curve fitted to the average value. The discontinuity which occurs at 87° is discussed below.

This curve can be compared with the similar curve which Chinnery and Toksöz (1967) constructed from a smaller number of events along the same profile. The curve that we present includes 171 events for which the delay times at all four stations in the F-ring of subarrays are available; Chinnery and Toksöz (1967, p. 204) included only 78 events on their curve. Our data are more complete in the intervals between 32°-40°, 51°-55°, and 72°-78°, which are of particular interest.

Figure 3 shows the comparison between a smooth curve fitted through our observed points and the corrected observations given by Chinnery and Toksöz (1967, Table 1, p. 215-216). For reference, Figure 3 also shows the Jeffreys-Bullen curve. Our curve includes only small adjustments required for smoothing. The Chinnery-Toksöz curve includes a constant correction of +0.05 seconds per degree to make the observations consistent with the absolute travel-times (see Chinnery and Toksöz, 1967, p. 214). The Jeffreys-Bullen curve was computed by fitting a 7-point polynomial to the J-B travel-times (see Chinnery and Toksöz, 1967, p. 204).

Comparison of the two observed curves shows three intervals in which Chinnery and Toksöz (1967) extrapolated their values (32°-40°, 51°-55°, and 72°-78°). The additional points on our curve demonstrate that the curve actually lies below the position that they suggest. In the intervals 32°-40° and 72°-78°, where their curve is projected above the corresponding portions of the J-B curve, the new data establish that the observed curve follows these portions of the J-B curve much more closely. For the interval between 52°-55°, where Chinnery and Toksöz place their curve only slightly below the J-B curve, our additional points suggest that this portion of the observed curve falls well below the Jeffreys-Bullen curve. The remaining portions of our curve, out to a distance of 87°, are in good agreement with Chinnery and Toksöz, except for the correction of +0.05 seconds per degree. This correction has not been added to our curve.

The segments along our curve which differ from the Chinnery-Toksöz curve are of particular interest. Chinnery and Toksöz (1967 p. 233) conclude from their results that the points where the slope increases abruptly (35°, 52° and 70° on their curve) reflect points of inflection in the velocity-depth function. They further conclude that these points of inflection occur at depths of approximately 800, 1300, and 2000 kilometers, respectively. The new detail provided by our values of p shows abrupt slope increases at 32°, 51°, 58°, and 71°. Our data thus indicate that: (1) on the northwest profile an additional point of inflection occurs in the velocity-depth function at a depth of approximately 1500 kilometers, and (2) the upper point of inflection occurs at a depth of approximately 750 kilometers.

Because our values of p were determined using only first arrivals they do not show any travel-time triplications directly, but they do show two features expected at triplication distances. These are: (1) relative absence of points where the slope increases rapidly, which may result from the reduced amplitude of the P wave arrival where triplication occurs; (2) relative abundance of points

in the interval immediately preceding the change in slope, as a result of focusing by the bottom of the velocity transition layer. Our curve shows a concentration of points in the intervals 29°-31°, 49°-51°, 56°-57°, and 68°-71° and a corresponding lack of points in the intervals 31°-33°, 51°-53°, 57°-58°, and 71°-72°.

The abrupt discontinuity in the curve of p vs distance for the northwest profile at 87° is probably due to a large change in epicentral azimuth of the corresponding events. All of the p values in the interval 83°-88° fall on the lower portion of the curve and the corresponding epicenters are in the range of azimuth 300°-308°. The epicentral azimuths of all the events in the distance interval 87°-97°, where the p values fall on the upper portion of the curve, are between 309° and 314°. Thus, the systematic change in the p-distance curve reflects a systematic change in the corresponding epicentral azimuths along the northwest profile.

SOUTHEAST PROFILE

The southeast profile includes 122 events in the range of azimuth 140°-160°. Forty other events whose epicenters lie on the profile were omitted because one or more stations in the F-ring did not record the signal. The 122 events finally included in the southeast profile satisfy all of the criteria for quality stated in the previous section.

Figure 4 shows the variation with distance of measured azimuth deviations along the southeast profile. Two important observations about azimuth deviations along this profile are: (1) the average value of +1.0°, and (2) a strong relationship with epicentral azimuths.

In the distance interval 38°-72° all of the epicenters are in the range of azimuth 142°-150° and all but three of the related values for azimuth deviations are between +0.9° and +2.5°. In the distance intervals 31°-38° and 72°-97°, where the epicentral azimuths change by more than 10°, the corresponding azimuth deviations also undergo the greatest rate of change.

Comparison of Figure 4 with Figure 1 shows that the azimuth deviation along the southeast profile is greater than along the northwest profile by at least 1.5°. This demonstrates a strong function of azimuth along both profiles.

Figure 5 shows the variation of p with distance for events along the southeast profile. The observed points provide good coverage of the distance range between 31° and 86° with the exception of the intervals between 39°-42°, 43°-45°, 47°-52°, 56°-60°, and 63°-66°. Five observed points in the interval 86°-97° establish the approximate position of this portion of the curve. All but four of the observed points along the southeast profile are within ±0.08 seconds per degree of the smooth curve fitted to the average value.

The lack of observed data in the above intervals creates

some doubt as to the actual position of the curve in these intervals. However, available data do show the following features along the southeast profile: (1) An abrupt increase in slope or an actual triplication is clearly indicated in the distance interval 34°-35°; (2) Similar abrupt increases in slope or triplications are suggested in the distance intervals 49°-54° and 63°-66°; (3) The distance interval 39°-42° may include such an abrupt increase in slope; (4) There are no clear indications of abrupt increases in slope at distances 32°, 58°, or 71°, where increases in slope were observed on the northwest profile.

Figure 6 shows a smooth curve fitted to p observed along the southeast profile, together with the observed curve for the northwest profile. The extrapolated distance intervals are shown by broken lines. Comparison of the two curves shows that the southeast profile curve is displaced from the northwest profile curve by an amount 0.48 seconds per degree, on the average. The position of the curve from the southeast profile after a constant correction of -0.48 seconds per degree has been applied is also shown in Figure 6.

Comparison of the northwest profile with the southeast shows: (1) the abrupt increases in slope which are clearly indicated at 32° and 71° on the northwest profile are not at all suggested by the data available from the southeast profile; (2) there are abrupt slope increases along the southeast profile in the intervals 34°-35° and 63°-66° which are clearly not indicated for the same intervals on the northwest profile; (3) it is possible that the abrupt increases in slope which occur at 51° and 58° on the northwest profile also occur at the same distances along the southeast profile, although the sparse data from the southeast profile suggest that such a change does occur between 53° and 54° but does not occur between 56° and 62°.

As for the northwest profile, each place where the p vs distance curve has an abrupt increase in slope reflects a corresponding increase in the velocity-depth function. Present data

from the southeast profile do not provide enough detail in the critical distance intervals to determine the actual depths at which these velocity transition zones occur. However, these data strongly suggest that three such velocity transitions occur beneath the southeast profile, at corresponding depths of approximately 800, 1350 and 1800 kilometers (these depth estimates are crude interpolations made using the figures of Chinnery and Toksöz, 1967). Similar transition zones have been previously observed in the upper mantle by many other workers (for example, Archambeau *et al*., 1967; Johnson, 1967; Anderson, 1967).

CONCLUSIONS

The average value of the observed azimuth deviations along the southeast profile is 1.5° greater than that for the northwest profile, and the observed p values for the southeast profile are greater than those for the northwest profile by nearly 0.5 seconds per degree. In addition, the observed discontinuity at 87° in the p curve for the northwest profile is apparently related to a systematic change in the epicentral azimuths, as described in Section II. These observations show that both wave-number parameters change considerably with changes in epicentral azimuth.

Azimuthal changes of this kind can result from either dipping layers or horizontal velocity gradients within the crust and upper mantle beneath the array. From a study of the relative station corrections at LASA, Fairborn (1966) has concluded that dipping layers cannot account for the magnitude of the required corrections but that horizontal velocity gradients may account for the required magnitude if they extend into the upper mantle. Thus we conclude that the azimuthal variation in p and azimuth deviation is probably caused by horizontal velocity gradients beneath LASA which extend into the upper mantle.

The observed variation with distance of p along both the northwest and southeast profiles shows abrupt increases in the slope of the curve at several places. However, the distances at which these changes occur are not the same along the two profiles. The additional detail provided by the new data from this study for the northwest profile suggests that abrupt increases in the slope of the p distance curves reflect several previously observed velocity increases within the mantle. For the northwest profile, our data indicate that four such velocity transitions zones occur, at depths of approximately 750, 1300, 1500, and 2000 kilometers. For the southeast profile the data are not as detailed, but they suggest that at least three such velocity zones occur at depths of approximately 800, 1350, and 1800 kilometers.

Thus, the new data presented here demonstrate that the velocity-depth function for the region extending northwest from LASA is distinctly different from that for the region to the southeast for depths between 700 and 2000 kilometers.

Departures of times from the least-squares plane wave front are the stations deviations. The results suggest additional work to determine if station deviations can be obtained as a function of azimuth and distance. The variation of p and azimuth deviations shown by this study suggest that the station deviations depend mainly on azimuth. However, it is possible that they also depend on distance to some extent.

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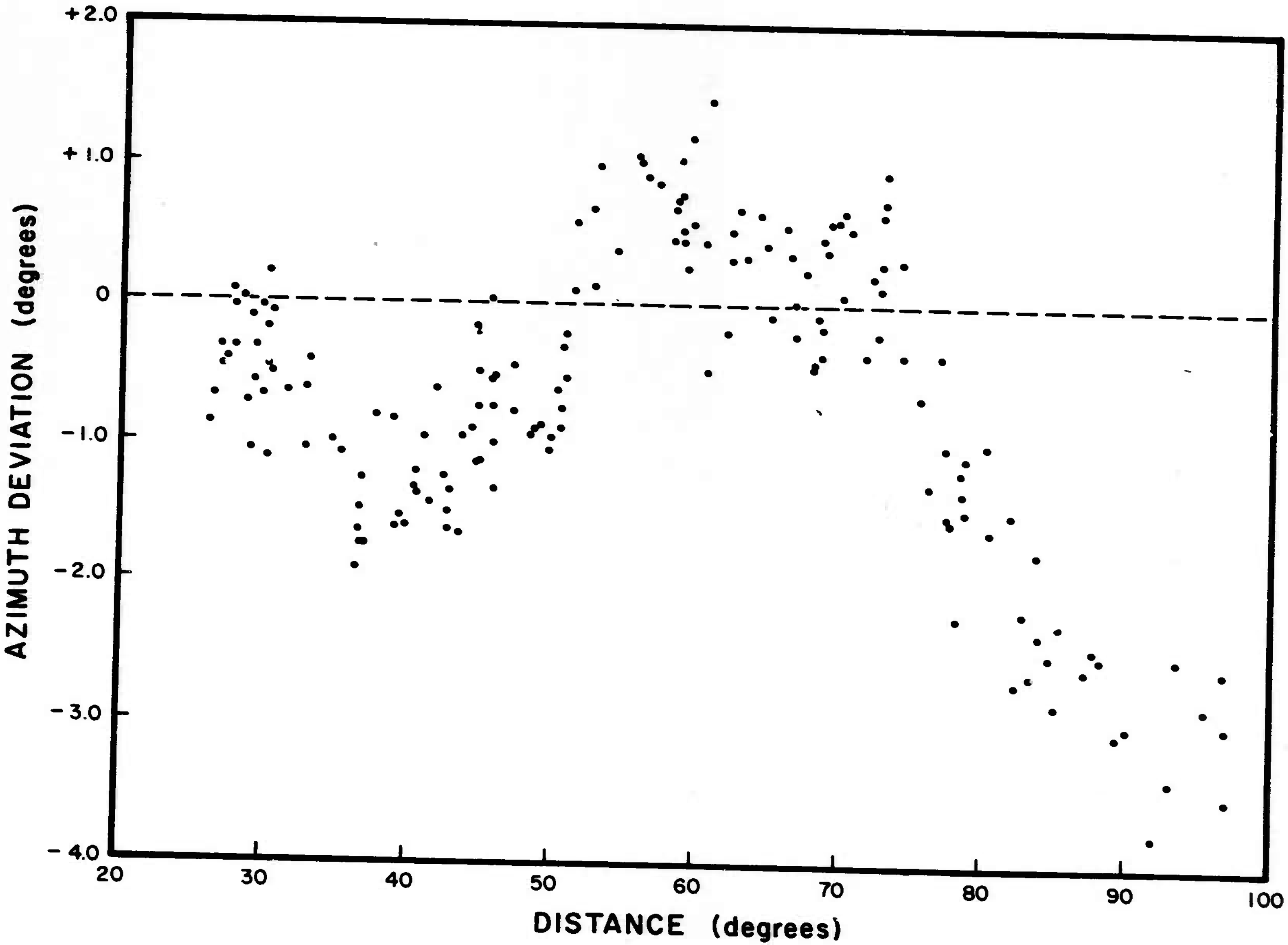

Figure 1. Observed azimuth deviations for events with epicenters located along the northwest profile, 300°-320°.

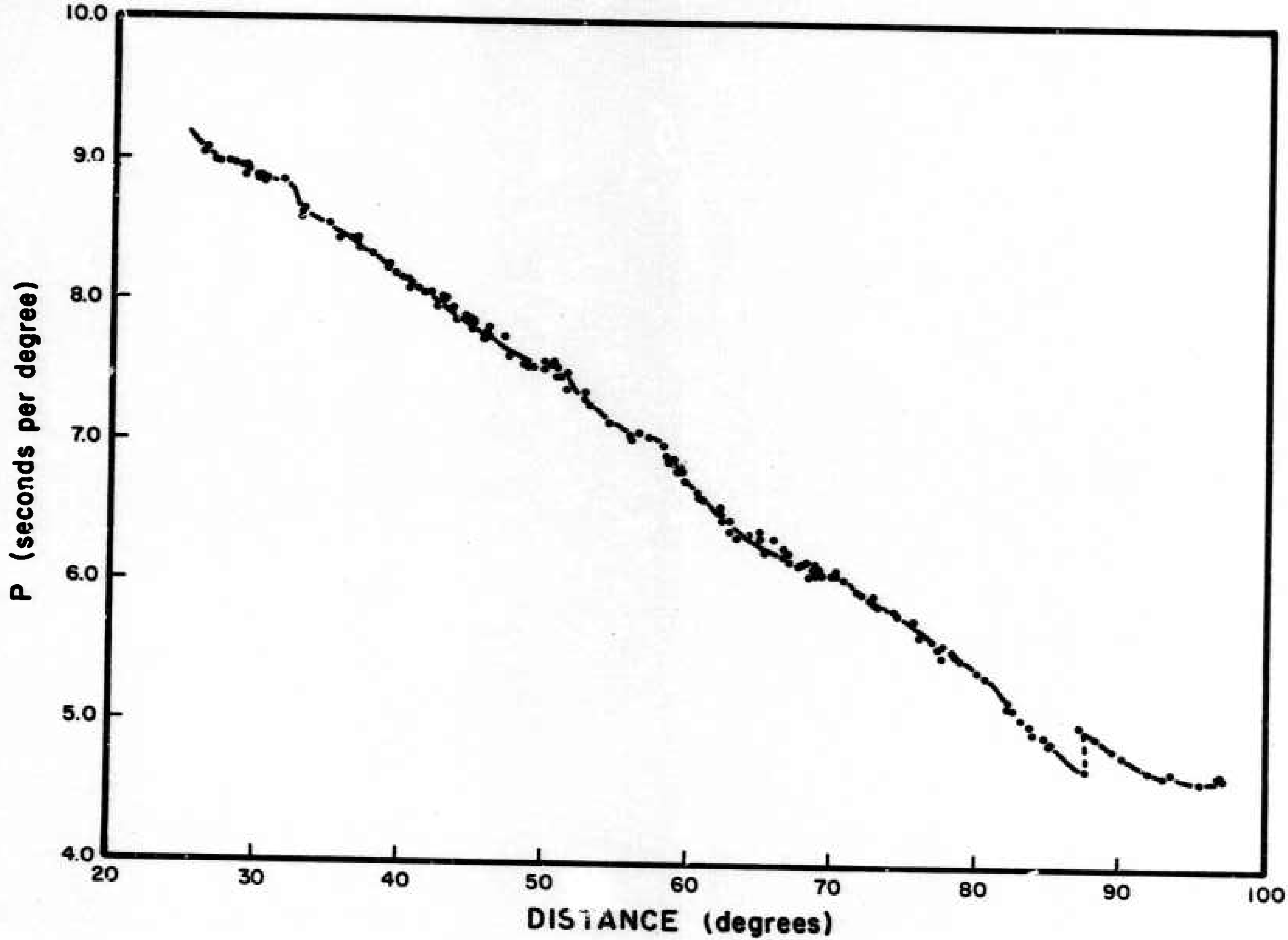

Figure 2. Observed values of p for events with epicenters located along the northwest profile, 300°-320°.

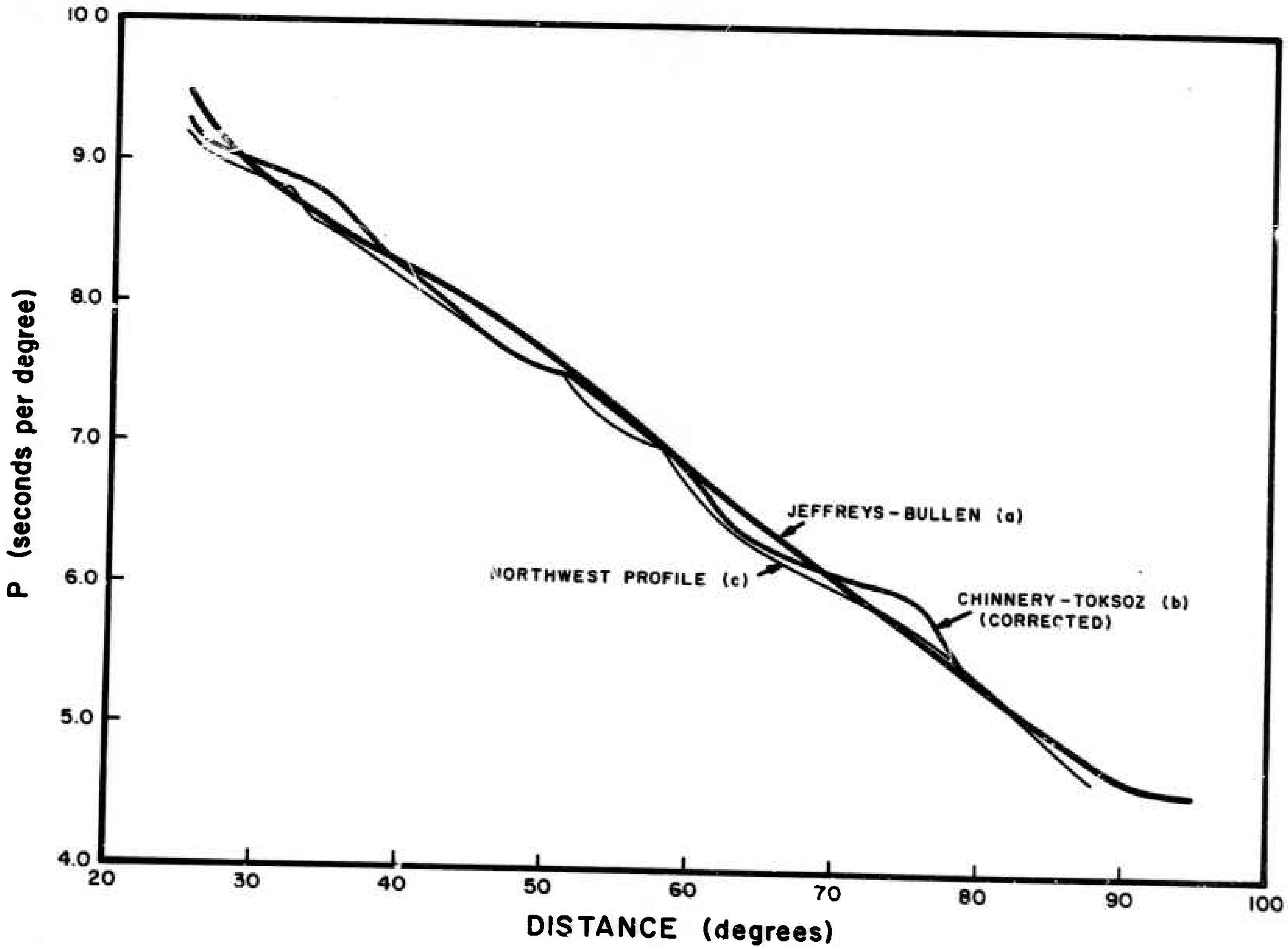

Figure 3. p versus distance curves

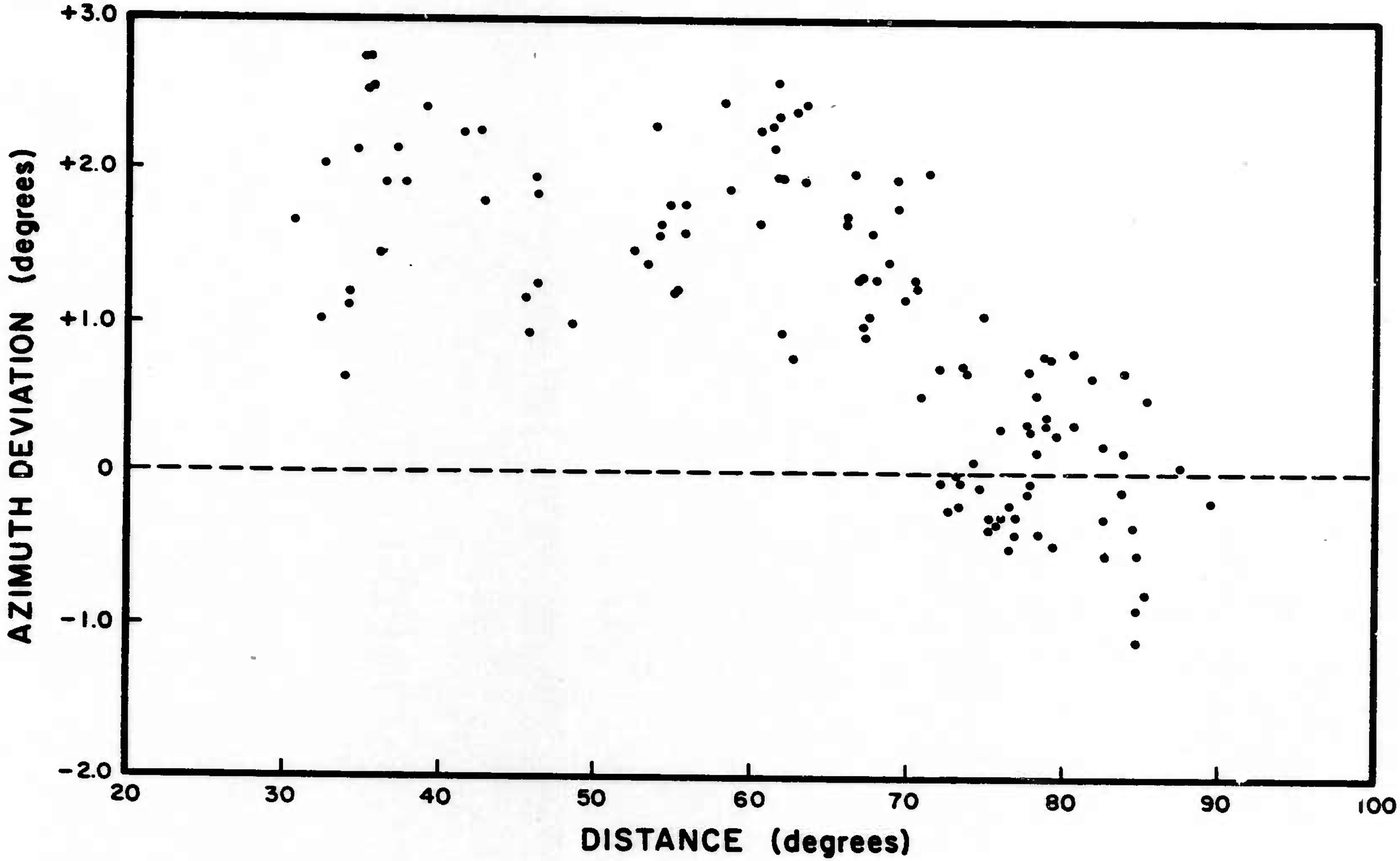

Figure 4. Observed azimuth deviations for events with epicenters located along the southeast profile 140°-160°.

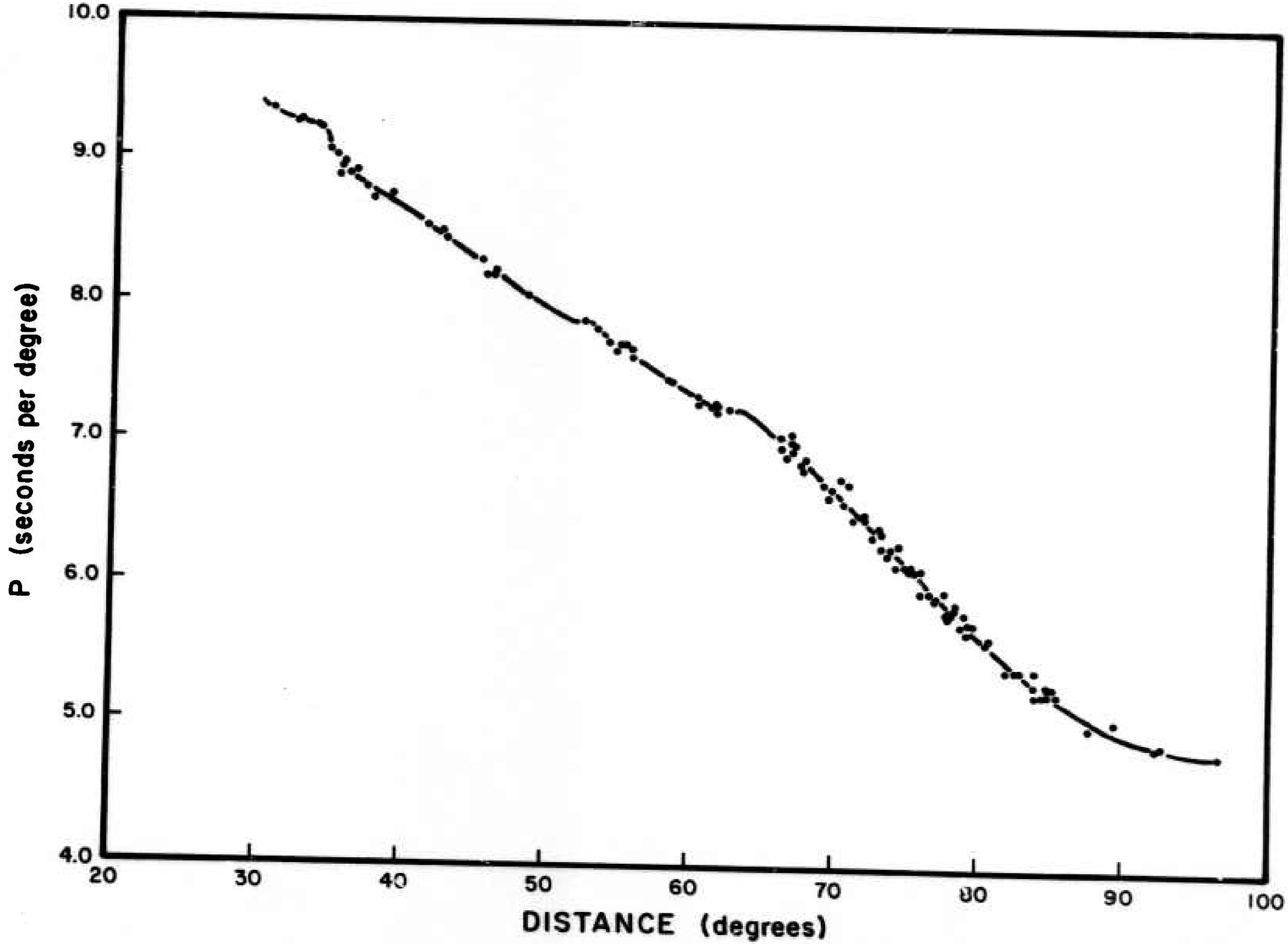

Figure 5. Observed values of p for events with epicenters located along the southeast profile, 140°-160°.

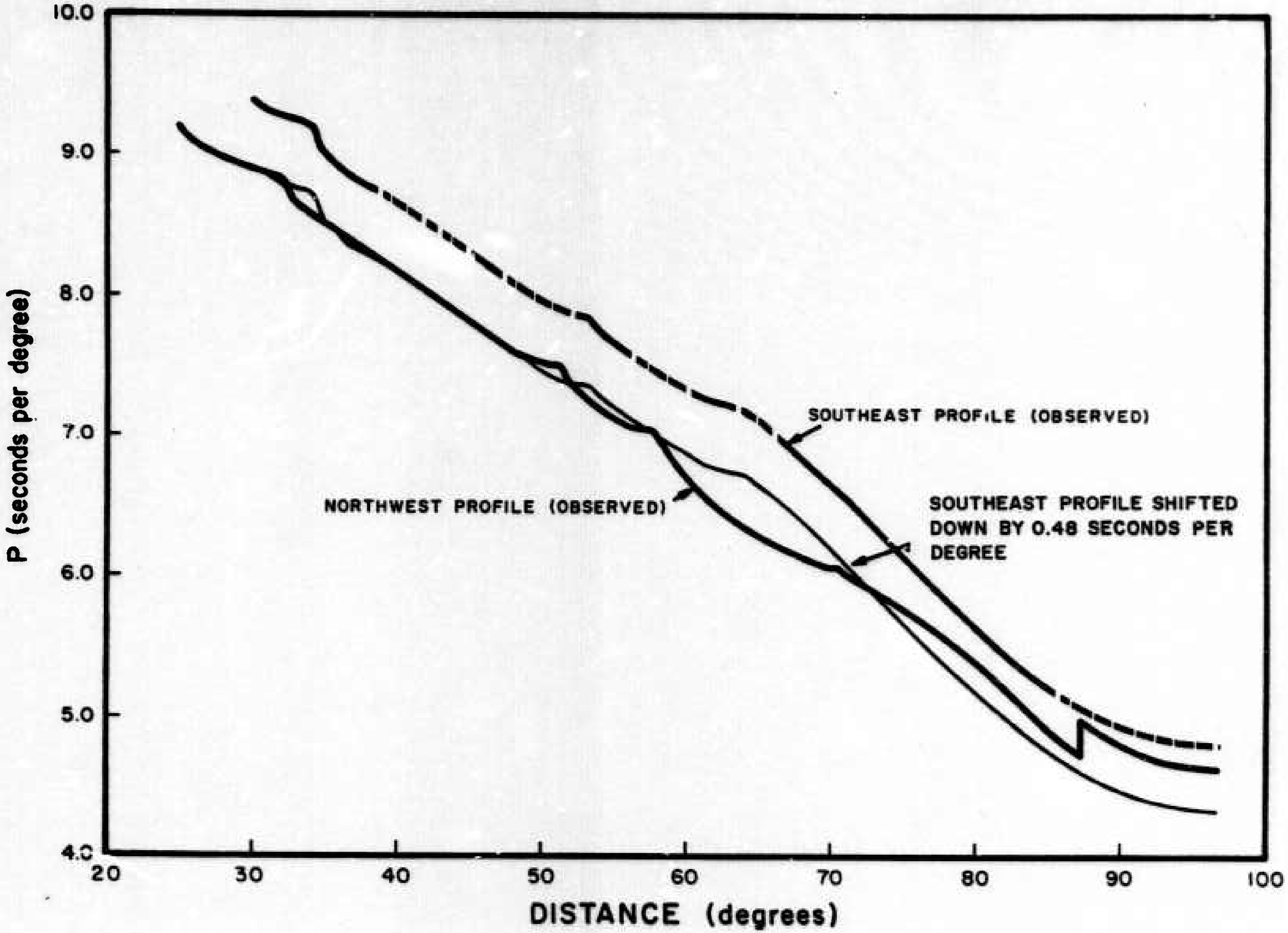

Figure 6. p versus distance curves

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